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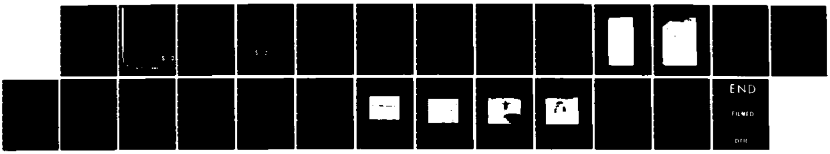

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Final Report

3D SENSOR FOR ADAPTIVE SUSPENSION VEHICLE

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Infrared and Optics Division

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This report describes the operation of an imaging optical radar system which measures the range to every point in its field of regard. The system is designed for use on the Adaptive Suspension Vehicle walking machine to provide local terrain 3D imagery for analysis to determine foot placement. The design specifications, system tests, measured performance and example imagery are presented.

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PREFACE

This report documents the final design, fabrication and check-out of the sensor conceptually designed under an earlier project entitled *"Three-Dimensional Vision System for the Adaptive Suspension Vehicle"* performed under DARPA Order 4468. A final report with that title was issued in January 1983 as ERIM Report No. 170400-3-F.

ACKNOWLEDGEMENTS

The authors express their thanks to the ERIM staff who participated in carrying out this effort. Special note goes to E. Grigg, J. Ladd and N. Griffin who constructed the sensor and to Dr. V. Larrowe for electronic design and engineering support. Professor R. M. McGhee and K. Waldron of Ohio State University provided invaluable guidance and technical support during the program. The stimulation and encouragement shown by Dr. Clinton Kelly, III, Program Director at DARPA, is also gratefully acknowledged.

TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

1
INTRODUCTION

The DARPA unconventional vehicle program supported research into techniques for creating a walking vehicle with sufficient agility to traverse rough, uneven terrain. The laboratory demonstration models of these machines were largely "blind", having only rudimentary knowledge of the terrain ahead gained from a few sensors.

The current Adaptive Suspension Vehicle (ASV) project at Ohio State University seeks to build a more autonomous vehicle in which the "subconscious" functions of attitude control and detailed foot placement for both forward and turning motions are controlled automatically. The driver can then give basic steering commands and perform overall navigation without having to individually control the legs of the vehicle.

Specifications for an on-board sensor were established in an earlier design study entitled "Three Dimensional Vision System for the Adaptive Suspension Vehicle" and reported in ERIM report 170400-3-F, January 1983. These specifications were derived from the system characteristics of the ASV itself. For example, the spatial resolution of the sensor is approximately the size of the ASV's foot, since this is the size stone or hole that must be sensed to approve a foothold. The frame rate (2 frames/sec) was derived from the maximum anticipated speed of 10 ft/sec and the desire to have a frame for each step of 5 ft. The range and field of view were established to allow multiple looks at potential footholds as they are approached. The volume, weight and power requirements were based on estimates of available space and power in the ASV.

This report describes the 3D terrain sensing unit as it was finally built for the ASV. Some changes were incorporated as the design was finalized, and some improvements have been identified for retrofit and future units.

2
SYSTEM DESCRIPTION

The ERIM 3D sensor shown in Figure 1 is an optical radar that measures the range to every point in the scene using a modulated GaAlAs laser. It has a field of regard of ±40° in the horizontal plane and covers a vertical field of regard (FOR) at depression angles of 15 to 75°. The sensor has an instantaneous field of view (IFOV) of 1°. This sensor is self-contained, including all power supplies and electronics. This is a turn-key system where the only control the operator has is the on/off switch. The laser system is eye safe when scanning. Interlocks prevent inadvertent operation when the system is disassembled or not operating properly. A picture of the 3D sensor with the cover removed is presented in Figure 2. The digital phase detector and computer interface electronics are mounted on the right side of the unit. From right to left across the picture background are the junction strip for power distribution, the power supplies, the RF electronics, and the nodding mirror drive electronics. From picture foreground to the background on the left hand side are the laser drive electronics and the nodding mirror motor drive. The system is rather compact, but most critical test points are easily accessible.

A simplified block diagram of the 3D sensor is presented in Figure 3. The 3D sensor consists of a scanning mechanism which directs the laser beam and field of view of the detector to the scene. The modulator driver provides a modulated light source via the laser and also a phase reference signal to the phase detector. The optical detector converts the reflected modulated optical energy to an electrical signal which is amplified and limited to remove amplitude information inserted by the varying reflectance of the scene. The limited signal contains phase but no amplitude information and is the other input to the phase detector. The output of the phase detector is the phase difference between the reference and reflected signals and corresponds to the range from the sensor to the target.

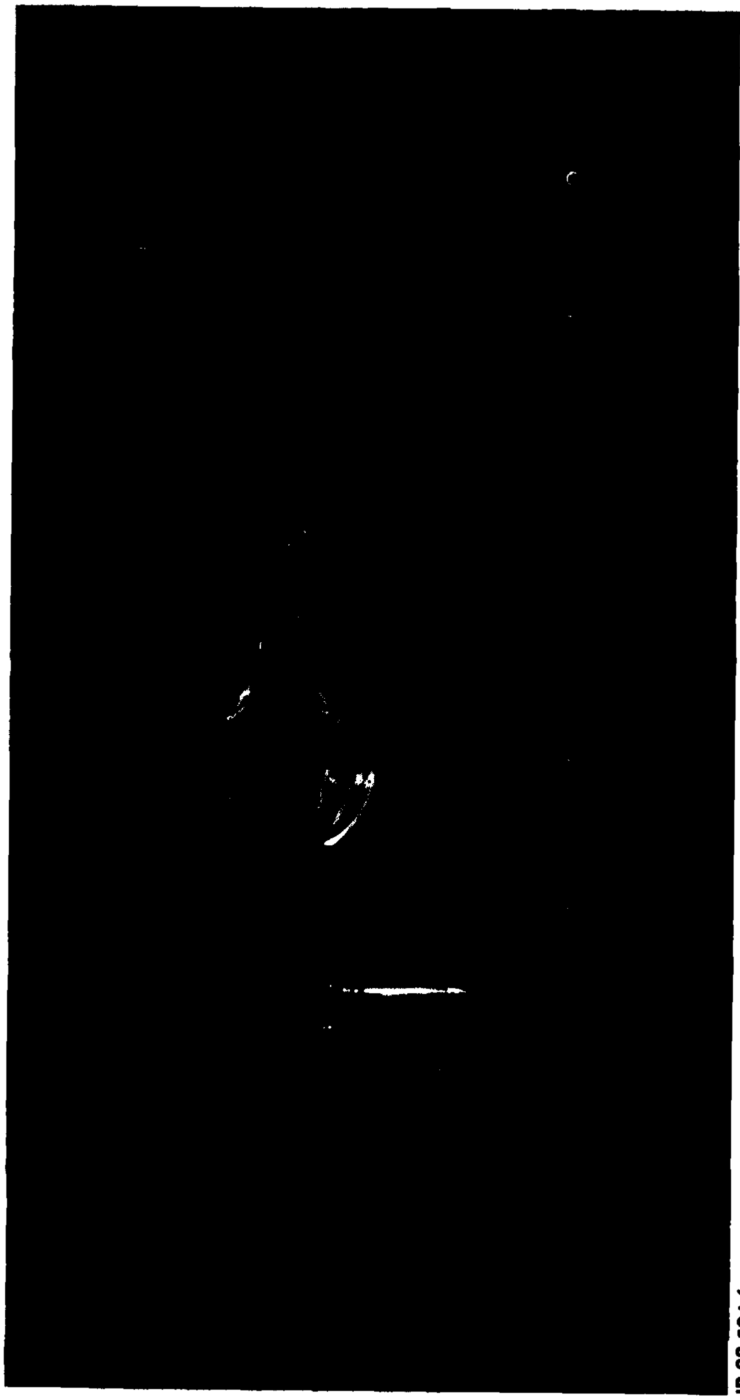

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FIGURE 1. SENSOR HEAD, FRONT VIEW

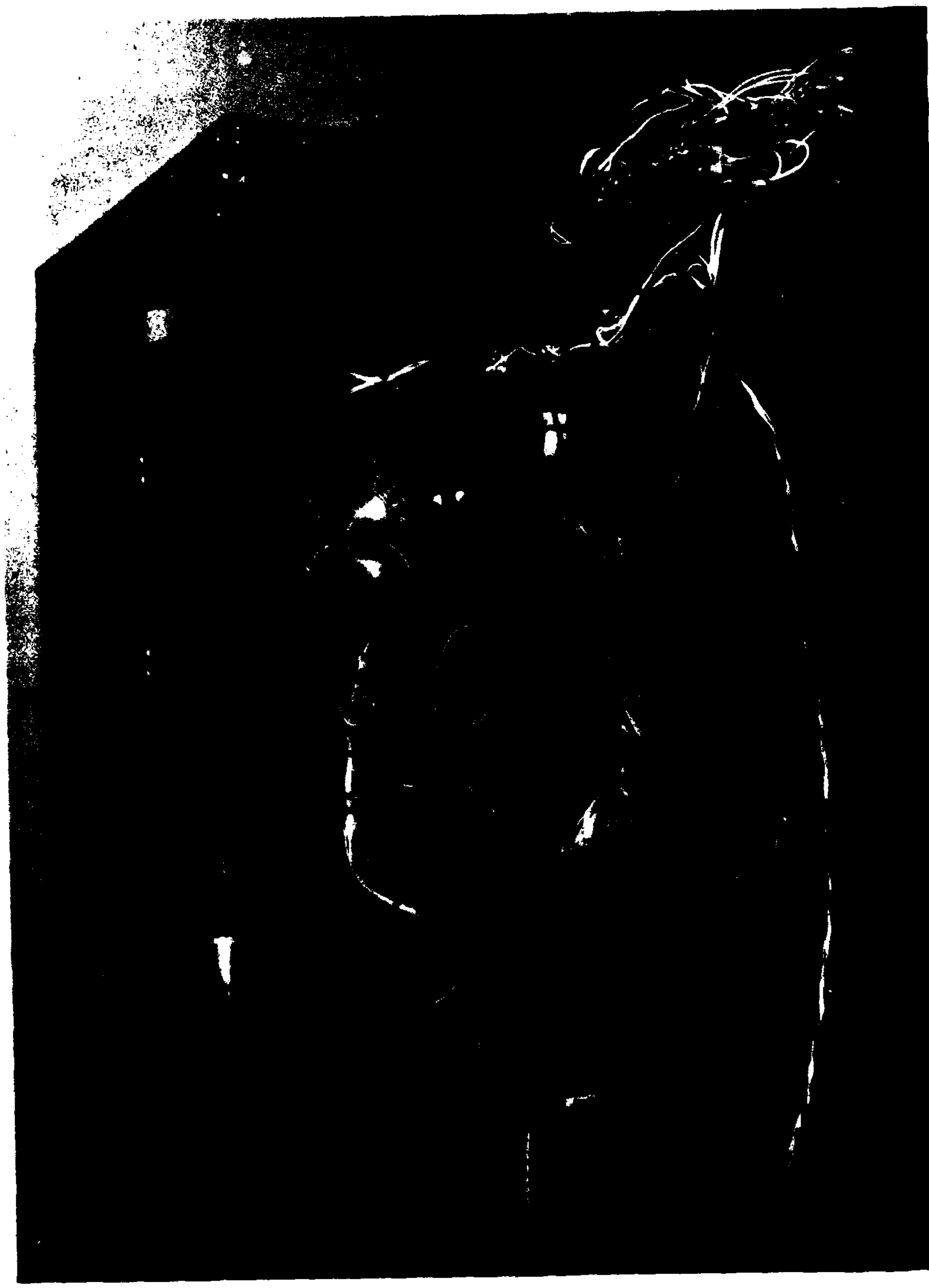

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FIGURE 2. SENSOR HEAD, REAR VIEW OF INTERIOR

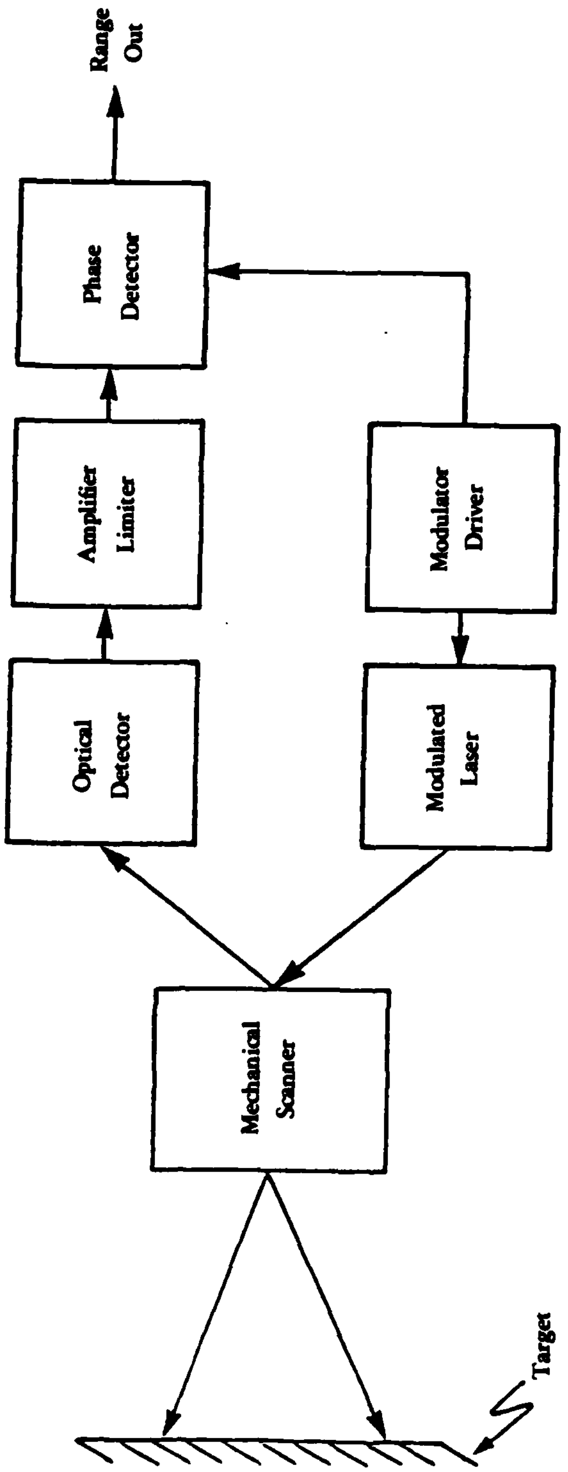


FIGURE 3. BLOCK DIAGRAM OF 3D SENSOR

The optical system of the 3D terrain sensor is depicted in Figure 4. The scanning mechanism consists of the nodding mirror and a 4-sided polygon mirror which together scan a raster from left to right, bottom to top. The polygon rotates at 80 revolutions per second, producing 320 scan lines per second. These are framed by the nodding mirror at 2 frames per second with 128 active scan lines per frame -- 32 scan lines are lost in vertical retrace. The inherent parallax caused by separate transmitter and receiver apertures is adjusted through alignment mirrors for a centerline intersection at 15 ft. An oversized IFOV for the receiver reduces the loss of received energy from parallax offset on near range terrain.

The transmitter optical train consists of a GaAlAs laser diode, collimating lens, anamorphic prism pair and a beam expansion telescope. The highly divergent elliptical output beam from the diode is collimated by a specially designed short focal length, low f/number lens. The beam is made circular by an anamorphic prism pair and is expanded in the telescope to create an output beam that increases in diameter to 6 in. at 30 ft.

The receiver optical train consists of telescope, a narrowband filter, and an avalanche photodiode. The telescope is focused at about 18 ft and produces a magnification of about 380X. The narrowband filter is matched to the peak of the laser diode and acts to eliminate background energy from the sun and other sources. The small avalanche photodiode chip and telescope determine the receiver IFOV at 12 in. for the 30 ft. range.

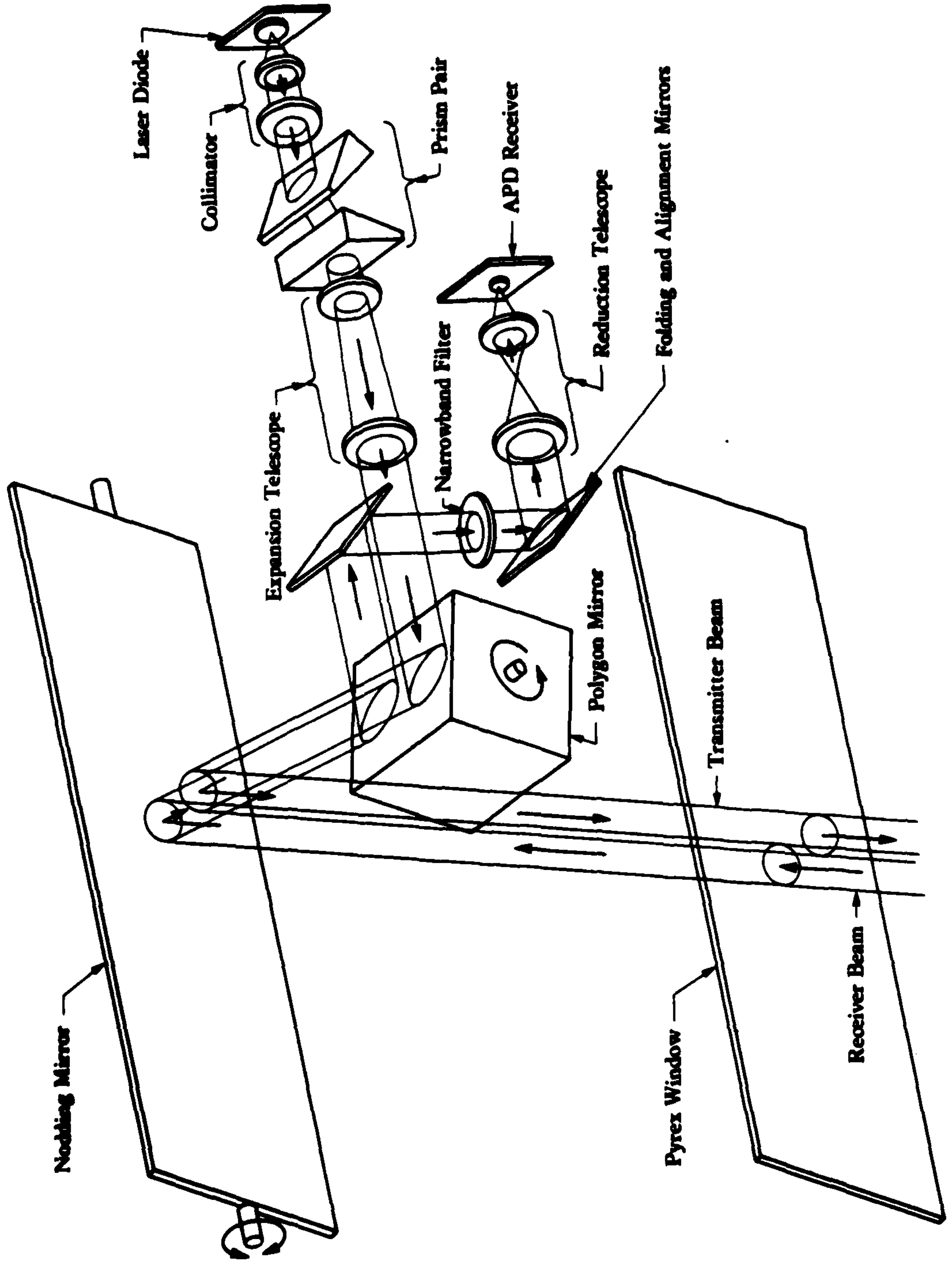


FIGURE 4. ASV OPTICAL SYSTEM

3
SPECIFICATIONS

The original design specifications and final measured performance for the 3D terrain sensor are presented in Table 1. The derivation of the specifications can be found in a report entitled "Three-Dimensional Vision System for the Adaptive Suspension Vehicle". The frame rate is 2 per second (same as the original design) with scanning from bottom to top.

To allow the vertical nodding mirror sufficient time to retrace to its start, the duty cycle was reduced from .9 to .8. This required increasing the instantaneous data rate to 92160 Hz. By buffering and reading out during the entire line time, the output data rate is reduced to 40960 Hz.

The field of regard, IFOV, and range resolution remain unchanged.

The sample rate is 92.160 kHz. The sensor samples 128 pixels per line which with a 1° IFOV and an 80° horizontal FOR produces a 37% overlap between pixels. In the vertical scan direction, 128 lines per frame produce a 53% overlap on the scan lines with a 1° IFOV.

The rms range noise is .26 ft. (8 centimeters) at a range of 30 ft. (9.14 m) from a 11% reflector in bright sunlight. The scanner output format is a 15-bit digital word where 8 bits represent the digital range and 7 bits represent the line count. The line count counts up to 127 and holds. It is reset to 0 upon the occurrence of the nodding mirror sync pulse.

The entire unit weighs 85 lb. and consumes approximately 450 w of 24 v dc power. The weight exceeds the original design because of the increase in nodding mirror size which resulted from extending the horizontal FOR, because extra electronics were required for driving the polygon scan motor. The actual power is less because of a conservative estimate of power consumption used in the preliminary design.

The physical size of the unit is 12.6 in. (32 cm) high by 21.6 in. (55 cm) deep including heatsinks and 26 in. (66 cm) wide. The depth measurement is taken from the front edge of the scanner and represents the projection of the top of the unit. As seen in Figure 1, the base of the unit is less than 21 in. deep. The unit is larger than the original design as a result of the increased FOV which requires larger mirrors.

A more detailed description of the 3D sensor is provided in the Operation and Alignment Manual for the system, ERIM Report Number 164700-5-T.

TABLE 1

Sensor Design and Measured Specifications

Parameter	Design	Measured
Frame Rate	2 per second	2 per second
Frame Scan	top to bottom	bottom to top
Data Rate	81920 Hz	92160 Hz Sampling 40960 Hz Buffered Output
Field of Regard (deg)		
Vertical	60	60 Depression angle of 15° to 75°
Horizontal	30	±40 Measured from centerline of sensor
IFOV (deg)	1	1
Range Resolution (ft)	.125 (3.81 cm)	.125 (3.81 cm)
Range Noise (ft)	.2 (6.1 cm) 10% target reflectance in bright sunlight	.26 (8 cm) 11% target reflectance in bright sunlight
Ambiguity Interval (ft)	32 (9.7)	32 (9.7)
Wavelength (μm)	.82	.82
Output Format	8 bits of range	8 bits of range, 7 bits line count
Power (W)	1000 24 Vdc	450 24 Vdc
Weight (lb)	50	85
Volume (ft)	3	Case Volume 2.96 12.6"H x 19.6"D x 26"W + connectors and heat sinks external
Mounting	TBD	4 - 10-32 bolts on the sensor baseplate

4
SYSTEM TESTS

Tests of the 3D sensor were conducted at ERIM to verify its operational characteristics. The scan rate of 92160 Hz was measured by monitoring the output of the digital clock with a frequency counter. The frame rate of 2 per second is derived from that clock and was verified by monitoring the synchronization pulses of the nodding mirror on an oscilloscope. Two pulses 1/2 second apart were observed.

The vertical and horizontal field of regard were determined by placing targets at the edges of the scene and determining when those targets were observable and then by using trigonometry to calculate the FOV of the system. The measurements verified a FOV of ±40° in the horizontal plane [21 ft. (6.4 m) at a range of 25 ft. (7.62 m) from the sensor]. A scan coverage of 1.6 ft. (.49 m) to 22.4 ft. (6.83 m) from the base of the sensor which was at a height of 6 ft. (1.83 m) confirmed the 15° to 75° depression angle (vertical FOR).

The IFOV was determined by overriding the interlocks and observing the laser spot produced from the sensor when the sensor was not scanning. The spot is readily observable using an IR image convertor. The spot was measured to be 6 in. at a range of 30 ft.

Range noise was verified by measuring a dark target and counting the number of levels of noise on the range signal and then calculating the rms noise level. A noise of 6 counts peak-to-peak out of 256 total counts was measured from a 11% reflective panel. Assuming a sinusodial noise distribution, this is an rms noise of 2.1 counts which corresponds to a noise level of .26 ft. (.08 m).

The ambiguity level was determined by moving a target further and further away and finding where it went through the ambiguity interval and then measuring the distance between the two points where the range readout has the same value. The ambiguity interval was measured as 32 ft.

The amplitude phase cross-talk was verified by arranging a target scene which consisted of a number of plywood panels each with a different reflectance surface. The average value of the range returned for all the panels did not change within the resolution unit of the system. This indicated that there was no amplitude phase cross-talk. Figure 5 shows an oscilloscope photo of the range output of the sensor.

Linearity was checked by observing steps of different ranges in the sensors field of view. By observing that a one-foot step remained a one-foot step and that a two-foot, four-foot, eight-foot step measured two, four and eight respectively, we determined that the sensor was linear and was operating as we had expected. A sample photo of the linearity test is shown in Figure 6.

Prior to delivery to OSU, a few frames of data were collected to verify the total sensor operation. Normally data are not presented as images to an analyst or to the ASV driver, but are intended for computer analysis to determine potential footholds for the vehicle. The terrain is scanned in an angle-angle-range format and the range is digitized to 256 levels which are difficult to display in the limited dynamic range of a CRT or photographic medium. The system is an extremely wide angle viewer and oversamples in both directions. This produces "fisheye" effects when the data are displayed without overlap or correction for angle effects.

Figures 7 and 8 are photographs of CRT displays for two frames of the test data. No geometric corrections nor dynamic range modifications have been applied. In Figure 7, a man is standing in front of a series of panels in the background near the top of the picture. Note that the panels are all the same level (range) indicating no amplitude range cross-talk, even though they had various reflectances and therefore different amplitude returns. Figure 8 is a rear view of a jeep showing clearly the steering wheel and the driver's seat. There is no passenger seat; however, other structural detail may be seen.

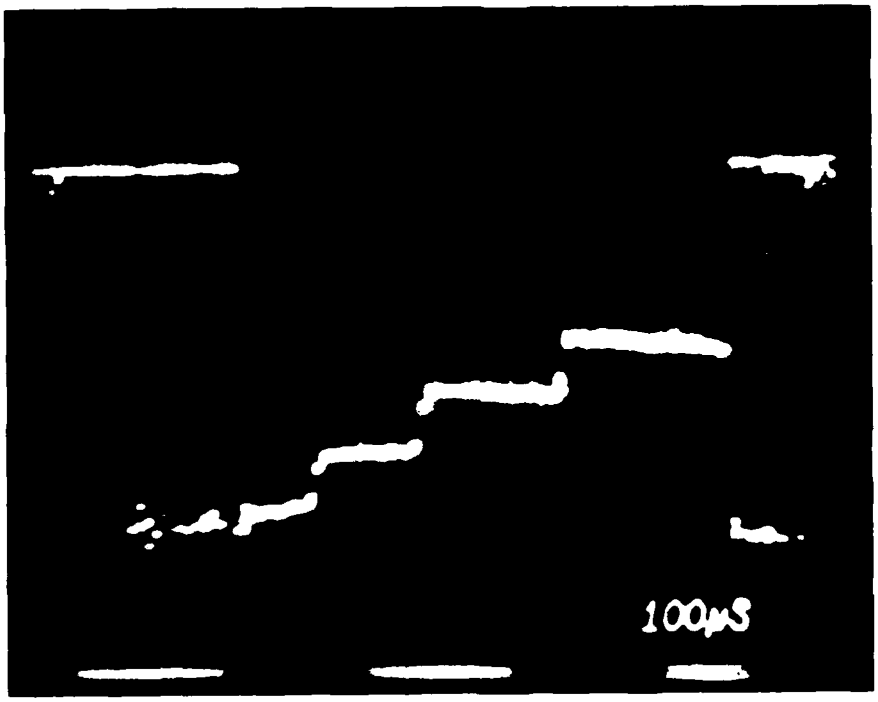
Range

Scan Angle

FIGURE 5. OSCILLOSCOPE PHOTO OF AMPLITUDE CROSSTALK TEST

Note: The Varying Range is Normal for Targets at a Constant Range as the Unit Measures in a Spherical Coordinate System

Range



Scan Angle

FIGURE 6. OSCILLOSCOPE PHOTO OF LINEARITY TEST

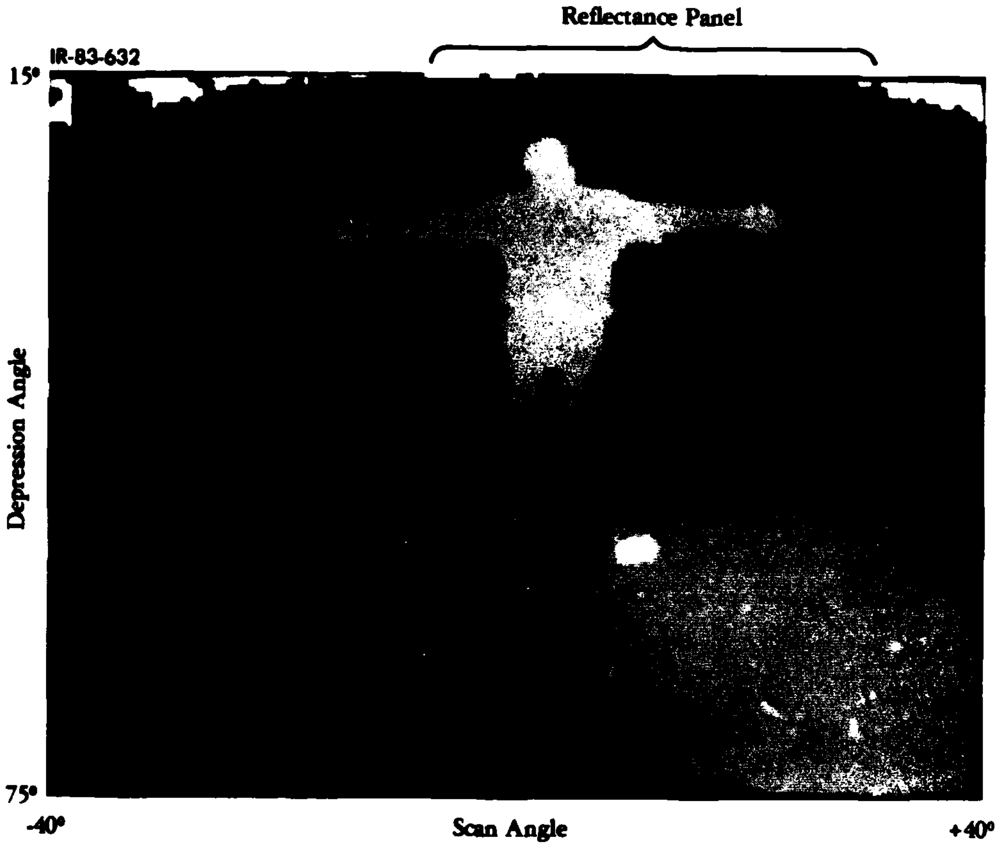


FIGURE 7. RANGE IMAGE OF MAN STANDING IN FRONT OF STEP REFLECTING PANEL ARRAY

FIGURE 8. UNCORRECTED RANGE IMAGE OF JEEP

5
CONCLUSIONS AND RECOMMENDATIONS

The ERIM 3D sensor for the 1984 ASV performs as expected. The unit passed the performance tests that had been set for it. There are two problems, however. One has to do with the scan motor and the other has to do with reflections from the window.

The scan motor was originally specified to take 1/3 less power than it presently consumes. A different type of motor would reduce the power consumption and would reduce the heating problem that exists. The present unit operates for about a half hour before the temperature builds up and shut-down occurs. By using a different type of motor, the power dissipation and temperature could be reduced significantly. We have submitted a plan to DARPA to correct this situation.

The second problem has to do with reflections off of the front window of the ASV sensor. Reflections from the front window are a problem in the center of the field of view. The first and second surface reflections enter the receiver path via scattering at critical angles of the scan mirror surfaces. If the optical surfaces were perfect, or at least better than they are, the scattered energy would not get onto the detector and would not cause problems. However, since the optics are not perfect the reflected energy gets into the system and causes an incorrect range reading when the light reflects back onto the receiver. There is also a problem where the light reflects back into the laser diode transmitter. The light reflected back into the transmitter causes the phase of the optical energy to change with respect to the electrical pump signal and hence produces an incorrect range reading. The reflection from the window can be solved by using a curved surface for the window. This correction will be made as a retrofit to the current ASV sensor.

The sensor is operating and has been interfaced to the computer at OSU. The system is operating as expected and should provide the data required for the ASV.

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